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Assessing the role of artificially drained agricultural land for climate change mitigation in Ireland

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A R T I C L E I N F O

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A B S T R A C T

In 2014 temperate zone emission factor revisions were published in the IPCC Wetlands Supplement. Default values for direct CO_2 emissions of artificially drained organic soils were increased by a factor of 1.6 for cropland sites and by factors ranging from 14 to 24 for grassland sites. This highlights the role of drained organic soils as emission hotspots and makes their rewetting more attractive as climate change mitigation measures. Drainage emissions of humic soils are lower on a per hectare basis and not covered by IPCC default values. However, drainage of great areas can turn them into nationally relevant emission sources. National policy making that recognizes the importance of preserving organic and humic soils' carbon stock requires data that is not readily available. Taking Ireland as a case study, this article demonstrates how a dataset of policy relevant information can be generated. Total area of histic and humic soils drained for agriculture, resulting greenhouse gas emissions and climate change mitigation potential were assessed. For emissions from histic soils, calculations were based on IPCC emission factors, for humic soils, a modified version of the ECOSSE model was used. Results indicated 370,000 ha of histic and 426,000 ha of humic soils under drained agricultural land use in Ireland (8% and 9% of total farmed area). Calculated annual drainage emissions were 8.7 Tg CO_2e from histic and 1.8 Tg CO_2e from humic soils (equal to 56% of Ireland's agricultural emissions in 2014, excluding emissions from land use). If half the area of drained histic soils was rewetted, annual saving would amount to 3.2 Tg CO_2e. If on half of the deep drained, nutrient rich grasslands drainage spacing was decreased to control the average water table at −25 cm or higher, annual savings would amount to 0.4 Tg CO_2e.

1. Introduction

The amount of organic carbon (OC) stored in soils up to a depth of 100 cm is considered to be nearly three times as large as the amount stored in aboveground biomass and twice the amount present in the atmosphere (Ciais et al., 2013). Success or failure at a global level to maintain or increase this stock will be decisive for mitigating climate change. In this respect, peatland soils play a pivotal role, covering only 3% of the global land area but estimated to contain between 20% and 25% of global soil organic carbon (SOC) (Smith et al., 2014). In intact peatlands, wet soil conditions impede aerobic biomass decomposition. Production is higher than decomposition and carbon is sequestered. The climatic effect depends on the timeframe applied: while over millennia peatlands have exerted a global cooling effect by removing long lived carbon dioxide (CO_2) from the atmosphere, under the 100-year timeframe used in international climate negotiations the emissions of short lived methane (CH_4) balance the carbon sequestration and result in a neutral or small global warming effect (Frolking and Roulet, 2007; Dise, 2009; IPCC, 2014). Therefore, the importance of peatlands for climate change mitigation is not in their potential for active carbon sequestration but relates to protecting their existing carbon stock. However, where peat soils are used for agriculture, artificial drainage facilitates cultivation and increases carrying capacity and yield. At the same time, increased aeration of the topsoil results in rapid decomposition of the organic stock and strongly increases emissions of CO_2 and nitrous oxide (N_2O). Like CO_2, N_2O is a long lived greenhouse gas (GHG). After carbon dioxide and methane it is the third most important gas contributing to global warming (Hartmann et al., 2013). Emissions of CO_2 and N_2O continue as long as soils remain in a drained state and elevated levels of OC persist (IPCC, 2014). These emissions are

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influenced by multiple management-, soil- and climatic factors like drainage depth, fertilization regime, mechanical stress, soil organic matter, redox potential, water filled pore space, pH or temperature (Coyne, 2008; Maljanen et al., 2010).

While the underlying processes are still not fully understood, emission levels of drained peatlands are of global relevance. Excluding emissions from South-East Asia, Joosten and Couwenberg (2008) calculated annual CO_2 emissions from agricultural peatland drainage at 900 million tons. Europe is considered to contribute more than a third to global emissions from agricultural peatland use (FAOSTAT, 2015).

While peat soils are the most prominent representatives, increased greenhouse gas emission following artificial drainage are also typical for other wet, carbon rich soils. In the definition of the Irish Soil Information System (SIS) used in this study, peat soils possess an organic layer with at least 20% OC and a minimum thickness of 40 cm. For histic soils, the minimum thickness is only 7.5 cm. In humic soils, minimum thickness is 7.5 cm and OC content is lower, but at least 3.5–6.0% (depending on the clay content) (Creamer et al., 2014). This study uses carbon rich soils as a collective term for both histic and humic soils. Drainage emissions are mostly unaffected by organic layer thickness above a critical value. For this reason, the IPCC uses the definition of organic soils where the thickness is 10 cm or higher and the minimum OC 12–18% (depending on clay content) (IPCC, 2014). On the other hand, the lower carbon content in humic soils clearly affects drainage emission intensities and results in much lower per hectare emissions of those soils.

Revised figures published in the IPCC Wetlands Supplement (2014) imply that CO_2 drainage emissions from organic soils in the temperate zone had been severely underestimated. Default values for direct CO_2 emissions from drained cropland sites were increased by a factor of 1.6 and for different grassland types by factors ranging from 14 to 24 (IPCC 2006, 2014). Considering all relevant emission pools, this increases the default annual emissions for cropland sites from 22.1 to 37.6 Mg $CO_2e\ ha^{-1}$ and for grassland sites from 4.7 to between 16.7 and 29.2 Mg $CO_2e\ ha^{-1}$.

Recent years have seen a strong increase in awareness amongst policy makers of the role that organic soils' carbon stocks plays for climate change mitigation. *Wetland drainage and rewetting (WDR)* was adopted as an optional accounting category during the second period of the Kyoto Protocol (2013–2020) (UNFCCC, 2011), allowing parties to obtain carbon credits for rewetting drained organic soils and reducing emissions. Even where this option is not chosen, rewetting is accounted for if it occurs under forests as a result of the mandatory forest management category (FM) or, where parties have elected to account for cropland management (CM) or grazing land management (GLM), if it occurs under the respective land uses. Accounting rules are designed to make electing to account for the land use sector attractive: electing to include additional emission categories does not result in tougher mitigation targets, even though with higher emissions in the reference year the relative emission reduction in percent will be lower. Furthermore, for WDR, CM and GLM net–net accounting is used, i.e. emissions in the year 1990 are subtracted from emissions in the current accounting year. Where emissions have remained constant, the budget is unaffected while emission decreases generate carbon credits.

At European climate policy level, changes in carbon stock of non-forest soils are currently not accounted for and rewetting of these soils cannot contribute to meeting Member States' obligations under the European Effort Sharing Decision (ESD). However, in 2014 the European Council announced that a new policy for including the land use sector into the Union's climate and energy policy framework would be finalized before 2020 (European Council, 2014). The new regulation will form the basis for including the land use sector into the European Union's intended nationally determined contribution (INDC) under the Paris Agreement. In 2016, the European Commission presented a legislative proposal intended to come into force in 2021(European Commission, 2016a). It aims to make accounting for cropland management and grassland management mandatory which includes accounting for drainage and rewetting on agricultural land. Accounting for managed wetlands can be elected as an additional accounting category. Analogous to regulations under the Kyoto Protocol, net–net accounting is to be used with the average annual emissions of the years 2005–2007 as reference amount. According to a second proposal for "binding annual greenhouse gas emission reductions by Member States“, a limited amount of carbon credits from the land use sector can be used to fulfil targets. (European Commission, 2016b). Rewetting of artificially drained organic soils may become an interesting mitigation measure, made even more attractive by the revised IPCC emission factors. The now increased difference in default emissions between drained and rewetted soils translates into an increase in carbon credits for rewetting.

This analysis builds upon the conceptual framework of Functional Land Management (FLM) defined by Schulte et al. (2014). FLM seeks to utilize land in a way that makes best use of its unique capabilities to deliver ecosystem services (MEA, 2005) in order to satisfy demand for these services at various geographical scales. The delivery of soil functions is determined by soil type and its complex interactions with land use. Under FLM, management of carbon rich soils must consider the high potential of these soils for providing climate regulating services through carbon storage. In order to assess this policy option, information on distribution of carbon rich soils, their land use, associated emissions and effects of drainage on economic performance are required. Usually, this data is not readily available and especially data on privately run drainage schemes is incomplete in many countries. Using the Republic of Ireland (Ireland) where agricultural drainage works are generally managed by land owners themselves and where registration of drainage schemes is not required as a case study, this article demonstrates how a dataset of policy relevant information for the management of this land resource can be created under conditions of limited data availability.

1.1. Objectives

The objectives of this study were to:

1) Assess the area of histic and humic soils artificially drained for agriculture in Ireland.
2) Assess drainage related GHG emissions from soils identified in 1) and analyse the contribution of different soil/land use combinations to total drainage emissions.
3) Calculate climate change mitigation potential of rewetting histic soils identified in 1) and assess associated income losses for pasture based beef farms.

2. Material & methods

2.1. Case study area

This study focuses on Ireland, and specifically on *cropland*, *managed grassland* and *other pasture* areas on poorly draining, carbon rich soils.

Agriculture plays an important role in Ireland, for both the country's economy and for its GHG emissions. Production is focussed on milk and beef for export, benefitting from low input-costs by using grass based feeding systems (Breen et al., 2010; Schulte and Donnellan, 2012). Of about 4.5 million hectares farmed, 81% is used for grass based production and 11% for rough grazing (DAFM, 2017). Bovines remain in the field for the major part of the year and milk production is aligned to the seasonality of the grass growth cycle (IFA, 2015). High rainfall rates combined with mild seasonal temperatures throughout the year allow for high levels of grass growth and make farmers largely independent from feed imports (Donnellan et al., 2011). However, where soils are poorly draining, high soil moisture rates cause problems for farmers, as they reduce both the length of the grass growing season through anaerobic conditions and options for grass utilization through risk of soil compaction (Schulte et al., 2012; Tuohy et al., 2015). Artificial drainage of those soils generally results in economic benefits to the farmers, reduces risk of compaction and can reduce diffuse pollution by altering runoff distribution amongst surface and subsurface pathways (Teagasc, 2013). However, the significance of this practice for GHG emissions and climate change is an emerging topic in both research and policy deliberations in Ireland (O'Sullivan et al., 2015).

According to data from SIS 50% of Irish land area can be classified as poorly draining. Temperate North Atlantic climatic conditions, in combination with effects of past glaciation and human influence have resulted in 1.5–1.7 million hectares being covered by peat soils (21%–25% of total land area) (Connolly and Holden, 2009; SIS, 2014). The role of these soils as major stores for SOC is well recognised. Estimates range from 1.1 to 1.6 billion tons of carbon, representing between 53% and more than 75% of Irelands total SOC stock (Tomlinson, 2005; Eaton et al., 2008; Renou-Wilson et al., 2011).

First state supported national drainage schemes date back to the end of the 19th century and it is assumed that all drainage works on organic soils have been initiated prior to 1990 (Burdon, 1986; Duffy et al., 2014). Today, new drainage operations on cropland or grassland require screening by the Irish Department of Agriculture if they either exceed 15 ha, are expected to have a significant impact on the environment, or affect actual or proposed natural heritage areas or nature reserves. This screening determines whether an environmental impact assessment is required. However, regulations pertain only to new drainage and not to the maintenance of existing drainage systems. Furthermore, the 15 ha criterion is most likely too high to effectively restrict drainage because not the area of drained fields but only the area of drains plus their immediate vicinity is counted (DAFM, 2011) and because Irish agriculture is dominated by small scale farms with an average size of 33 ha. Only about 3% of farms are bigger than 100 ha (Irish Central Statistics Office, 2012).

Ireland has elected to account for CM and GLM in the second accounting period of the Kyoto Protocol. Because drainage system were installed before the reference year 1990, Ireland is not accountable for on-going emissions but receives carbon credits under the net–net accounting as original drainage has been reduced with a decline of the total area of agricultural land use. However, any emissions from new drainage on agricultural land would have to be accounted for.

2.2. Datasets

2.2.1. Irish Land Use Map

We used the Irish Land Use Map (LUM) generated by O'Sullivan et al. (2015) which delineates agricultural land use categories based on the FLM framework (Schulte et al., 2014). This map combines spatial data from the Irish Land Parcel Information System (LPIS), Forest Service and National Parks and Wildlife Service (NPWS). Protected areas are mapped combining actual and proposed areas for environmental conservation as proposed areas in Ireland are legally protected from the date they are proposed (NPWS, 2015). O'Sullivan et al. (2015) did not assume drainage within protected areas. However, we found an overlap between protected areas and land benefitting from major public drainage schemes. Furthermore, drainage works that already exist when areas become protected are usually not affected by the sites' new status. We therefore elaborated on previous analysis by also mapping agricultural land use within protected areas.

2.2.2. Irish Soil Information System

The SIS of 2014 contains the most up to date information on soils in Ireland. It has been prepared at a scale of 1:250,000 by applying predictive mapping techniques and validating results through a 2.5 year field survey, including analysis of 11,000 soil auger samples (Creamer et al., 2014). Based on dominant soil forming factors and diagnostic features, Irish soils are divided into 11 great groups and 66 subgroups. All subgroups fall into one of five drainage classes (ranging from excessive to poorly draining) and can be classified by their organic carbon content.

The smallest classification units are 213 individual soil types. However, their spatial variability does not allow for mapping at the 1:250,000 scale. For mapping purposes, they are grouped into a total of 58 soil associations which each consist of 2–12 soil types that commonly occur together in the Irish landscape. The proportionalities of the soil subgroups within each association are known at national scale (Creamer et al., 2014).

2.3. Terms and definitions

In this paper, the terms "draining" and "drainage class" (e.g. poorly draining) refer to the natural infiltration capacity of soils while "drainage" and "drained" refer to an artificial lowering of the water table through technical measures. Following the definition in the IPCC Wetlands Supplement, we distinguish between "shallow drained" soils where the average annual water table (over several years) remains above −30 cm and "deep drained" soils, where it is lower.

2.4. Locating carbon rich soils drained for agriculture

In a first step, all soil associations were selected where at least 50% of the subgroups were poorly draining, carbon rich soils. Two scenarios were distinguished: V1 considers only histic soils while V2 considers both histic and humic soils. Lithosol subgroups were not counted because drainage of shallow soils is technically difficult and therefore uncommon. For the same reason, areas with a gradient steeper than 12^0 were removed (c.f. Mockler et al., 2013), using a digital elevation model with 20 m resolution (Preston and Mills, 2002).

Second, a representative agricultural land use profile for histic and humic soils in Ireland was established by intersecting the selection with the LUM (O'Sullivan et al., 2015), using ArcMap 10.1. Polygon slivers smaller 100 m^2 were removed by joining them to the neighbouring polygon with which they shared the longest border.

2.5. Share of artificial drainage for different management types

Agricultural drainage works in Ireland are generally managed by land owners themselves and there is no requirement to register drainage schemes. For this reason, few records or maps exist and exact share, quality or type of drainage on today's agricultural land is unknown. In their Land Drainage Map, Mockler et al. (2013) assume artificial drainage for all poorly draining agricultural soils below 200 m OED and with a gradient lower than 12°. This equals artificial drainage on 44% of all agricultural land, or on 29% of the total land area. These estimates are in line with earlier values published by Burdon (1986), who calculated the total area drained as covering 29.3% of the country. For our scenarios, we follow the reasoning of Mockler et al. and assume all *cropland* and *managed grassland* areas on poorly draining soils to be artificially drained unless shallow soils or slope prevent such measures. However, our land use category *other pasture* includes rough grazing on non-grassland sites like heath. These sites are usually not profitable enough to merit the effort of drainage. Based on interviews with practitioners and drainage experts, we assume a drained share of only 15% for these sites and explore the effect of our assumption in a sensitivity analysis.

2.6. Emissions from histic soils

2.6.1. Calculation & emission factors

Generic (Tier 1) emission factors for *organic soils* (IPCC, 2014) were used to calculate emissions from drained and rewetted histic soils. Though the minimum thickness of the carbon rich layer is lower for histic soils than for organic soils, the vast majority of histic soils in

Table 1
Emission factors [Mg CO_2e ha^{-1} yr^{-1}] of drained and rewetted organic soils in the temperate zone, calculated from IPCC (2014).

			Drained						Rewetted	Δ Rewetted - Drained
Land use	Nutrient status	Drainage depth	CO_2 soil	CO_2 offsite (DOC)	CH_4 ditches (5% of area)	CH_4 soil (95% of area)	N_2O soil	Total	Total	Total
Cropland	poor	n./a.	28.97	1.14	1.46	–	6.09	37.65	3.1	−34.5
Cropland	rich	n./a.	28.97	1.14	1.46	–	6.09	37.65	9.9	−27.7
Grassland	poor	shallow	19.43	1.14	0.66	0.04	2.01	23.29	3.1	−20.2
Grassland	poor	deep	19.43	1.14	1.46	0.04	2.01	24.08	3.1	−21.0
Grassland	rich	shallow	13.20	1.14	0.66	0.93	0.75	16.67	9.9	−6.8
Grassland	rich	deep	22.37	1.14	1.46	0.38	3.84	29.18	9.9	−19.3

Ireland are peat soils with a layer thickness of at least 40 cm. Potential errors derived from different soil terminologies are therefore assumed to be negligible.

Direct CO_2 emissions, offsite CO_2 emissions from dissolved organic carbon (DOC) in drainage water, CH_4 emissions from both soils and open drainage ditches, as well as direct nitrous oxide (N_2O) emissions from soils were considered. The IPCC also lists fire emissions as a drainage related emission category. However, they were not included because fire emission factors are not directly related to the area of drained land. In accordance with UNFCCC reporting conventions, CO_2 equivalents (CO_2e) of CH_4 and N_2O emissions were calculated at 25 and 298 respectively, based on their global warming potential over a 100 year timescale (UNFCCC Decision 24/CP.19; IPCC, 2007).

Eq. (1) explains how emissions from drained and rewetted histic soils were calculated in this study while Table 1 shows the IPCC default emission factors for drained and rewetted inland organic soils (IPCC, 2014).

Calculation of GHG emissions from drained and rewetted histic soils in Ireland

$$\text{Emissions} = \boldsymbol{A}^*(\boldsymbol{EF}_{\boldsymbol{CO_2\ soil}} + \boldsymbol{EF}_{\boldsymbol{CO_2\ offsite}} + \boldsymbol{EF}_{\boldsymbol{CH_4\ ditches}} + \boldsymbol{EF}_{\boldsymbol{CH_4\ soil}} + \boldsymbol{EF}_{\boldsymbol{N_2O\ soil}}) = \boldsymbol{A} * \boldsymbol{EF}_{\textbf{Total}} \quad (1)$$

where:

A: Area of drained/rewetted histic soils

$\boldsymbol{EF}_{\boldsymbol{CO_2\ soil}}$: Emission factor for direct CO_2 emissions

$\boldsymbol{EF}_{\boldsymbol{CO_2\ offsite}}$: Emission factor for offsite CO_2 emissions from DOC in drainage water

$\boldsymbol{EF}_{\boldsymbol{CH_4\ ditches}}$: Emission factor for CH_4 emissions from drainage ditches; this factor is set to 0 for rewetted soils

$\boldsymbol{EF}_{\boldsymbol{CH_4\ soil}}$: Emission factor for CH_4 emissions from soils

$\boldsymbol{EF}_{\boldsymbol{N_2O\ soil}}$: Emission factor for direct N_2O emissions

$\boldsymbol{EF}_{\boldsymbol{Total}}$: Emission factor defined as the sum of the above emission factors

2.6.2. Nutrient status and drainage depth

The vast majority of Ireland's histic soils are ombrotrophic blanket bogs and raised bogs (~1.6 million hectares). Hammond (1981) records only 93,000 ha of minerotrophic fens, of which 77% have by now been drained and reclaimed for agriculture (Foss, 2007; Irish Peatland Conservation Council, 2015). While the IPCC (2014) recommends as a default to treat ombrotrophic sites as nutrient poor and minerotrophic sites as nutrient rich, this is not considered to be representative of the Irish situation where the nutrient status of many sites has been strongly influenced by long term nutrient management. For the calculations of this study, an equal mix of nutrient poor and nutrient rich sites was therefore assumed.

In the absence of reliable information on drainage depth, the IPCC (2014) recommends to assume deep drainage. In the Irish context, this would lead to a strong overestimation of emissions as not all drainage installations are well maintained. Additionally, a vast proportion of drainage works was installed without any site investigation and instead was informed by local norms with respect to drainage type, depth and spacing, possibly resulting in low drainage efficacies (Mulqueen and Hendriks, 1986). For the calculations of this study, an equal share of deep drained and shallow drained sites was assumed. The effect of assumptions for nutrient status and drainage depth was explored in a sensitivity analysis.

2.7. Emissions from humic soils

Emissions from humic soils are, with the exception of long term effects of cropland use, not covered by IPCC emission factors and not reported under the UNFCCC. We calculated emissions from humic soils, analogous to the Tier 1 method described in Eq. (1), as the product of the area of drained humic soils and emission factors. To generate emissions factors, a modified version of the ECOSSE model (version 5.0.1) was used (Smith et al., 2010). ECOSSE is based on two models originally developed for mineral soils: RothC for soil C (Jenkinson and Rayner, 1977) and SUNDIAL for soil N and soil water (Bradbury et al., 1993). The combined model has been developed to simulate carbon- and nitrogen cycling, as well as GHG fluxes (Smith et al., 2010). ECOSSE describes soil organic matter as five pools (inert organic matter, humus, biomass, resistant plant material and decomposable plant material). Material is exchanged between soil organic matter pools during decomposition, using first-order rate equations and a specific rate constant for each pool. Transfer of organic matter from one pool to another is dependent on temperature, moisture, soil organic matter inputs (plant growth) and soil pH. Emissions were modelled for four soil types representative of the humic soils in the selected associations. Soil physical and chemical data were taken from published and unpublished data of SIS while weather data was taken from synoptic weather stations of the Irish meteorological service. Weather stations were selected by calculating Thiessen polygons around all stations and choosing those where the polygon had the greatest overlap with the respective soil/land use categories.

For the undrained situation, the water table was set at −10 cm (near saturated conditions), for the drained situation, the water table water was dropped to −1.5 m (drainage system representing deepest piped drains used). Extreme values were chosen to show the full range of drainage related emissions. Because the model is sensitive to the distribution between recalcitrant and labile carbon pools, the model was first run for 10,000 years to allow both pools to reach equilibrium. The total SOC estimated by a 10,000 year run using default plant inputs was compared to the total measured SOC in order to optimise organic matter inputs so that simulated steady-state SOC matches the measured values. After that, soils in the model were drained.

For estimating emissions from *managed grassland* and *other pasture*, simulated management for all four soils consisted of re-sowing with grass after drainage, fertilization with 25 kg N $ha^{-1}yr^{-1}$ and grazing by cows at a stocking rate of 0.7 livestock units. This is representative of low fertilizer input and very low stocking rate, as the Irish average for cattle rearing farms is 1.3 livestock units per hectare (Dillon et al., 2017). For *croplands*, simulated management consisted of inversion ploughing, continuous spring barley cultivation and fertilization with

140 kg N ha^{-1} yr^{-1} in equal splits during April and late May. Barley grain and straw were considered to be removed and stubble ploughed in during the next growing season. This was done for only one soil type because *cropland* has a very low share of land use in the selected associations and effects of this land use category on total emissions were considered to be small. The model was run for 30 years after drainage without reaching a new soil carbon equilibrium. Annual CO_2 emissions were determined by calculating the difference in soil carbon stock before and after drainage and dividing it by the 30 years period. Annual CH_4 and N_2O emissions were modelled directly. However, because modelled N_2O emissions were not only a result of drainage but also influenced by fertilizer applications, they were not considered in the calculations of this paper. This results in a slight underestimation of total drainage emissions, as modelled N_2O emissions increased with drainage.

2.8. Emission saving from rewetting

Potential GHG savings from rewetting were calculated only for those soils and land uses where the IPCC provides emission factors and rewetting can generate credits under Tier 1 accounting. This includes the full rewetting of histic soils under cropland and grassland, as well as reducing the drainage depth in nutrient rich, histic grasslands to turn deep drained sites into shallow drained sites. Emission savings were calculated by comparing emissions before and after rewetting. Under Tier 1 accounting, no transition period is used. This is a strong simplification as greenhouse gas emissions may even rise for a short period of time after rewetting before reaching a new, lower equilibrium (Kløve et al., 2017).

2.9. Economic costs of rewetting

Economic effects of rewetting were calculated by assuming a change from well-draining to poorly draining soil conditions. This reduces the number of days with a positive soil moisture deficit (SMD), or dry days, and restricts grass utilization for pasture based agriculture. Based on Crosson et al. (2009), costs to the farmer in extensive beef systems (1 cow per hectare) was estimated at €1.54 ha^{-1} per dry day. Modelled data of the median number of dry days for well- and poorly draining soil conditions at 104 locations throughout Ireland was supplied by the Irish Department of Agriculture (T. Harty, pers. comm.). Information on the dataset is found in Schulte et al. (2012) and O'Sullivan et al. (2015). Point data was extrapolated using the inverse distance weighted method with five points and a power of two. Results were intersected with the combined soil/land use map to determine the average number of dry days under drained and under rewetted soil conditions.

3. Results

3.1. Spatial distribution and emissions from drained carbon rich soils

For scenario V1, only the peat association (1XX) fulfilled the selection criterion. For scenario V2, four Gley associations (0660c, 0700b, 0700f, 0760f) and one Podzol association (0843f) were also selected. However, the area of the peat association is still dominant in V2. Table 2 shows area and subgroup proportionalities of the selected associations while Fig. 1 shows their geographic distribution (a,b) and agricultural land use (c,d).

Cropland, *managed grassland* and *other pasture* make up 56% of the peat association and on average 76% in the other, predominately humic associations. Fig. 2 shows their relative importance: *Other pasture* is the dominant type of agriculture for the histic soils (72%) while for humic soils *managed grassland* is the main land use (85%). *Cropland* plays only a very minor role in both groups (1%). Agriculture within protected areas is very relevant for the histic soils (28%) but constitutes only 5% of agricultural land use on the humic soils.

Table 3 shows the ECOSSE modelling results and the derived emission factors for humic soils.

While drainage significantly reduced modelled CH_4 emissions (even resulting in net uptake in most cases), positive climate effects were outweighed by the increase of CO_2 emissions from accelerated SOC decomposition. Annual emission factors were 8.3 Mg CO_2e ha^{-1} for the *cropland* site and 2.6–7.2 Mg CO_2e ha^{-1} for the *managed grassland* sites.

Table 4 shows the area of drained carbon rich soils in Ireland and emissions resulting from drainage. Please note that the dominant land use on histic soils is *other pasture* where only 15% of the land is assumed to be drained. This means that of 918,000 ha of agricultural land use in scenario V1 only 358,000 ha are considered drained. For the predominantly humic associations, please also note that *only a share* (c.f. Table 2) of each soil association's land area is humic soils. Of the 341,000 ha of agricultural land within the selected associations, 208,000 are considered drained.

While poorly draining, carbon rich soils have a share of more than 50% in the selected associations, these soils also constitute minor factions within other associations: 55,000 ha of histic soils (3%) exist outside association 1XX and 315,000 ha of humic soils (51%) exist outside the selected Gley and Podzol associations. Area and emissions of these minor factions were included in calculations by assuming the same land use distribution for them as on the selected associations.

Annual GHG emissions from drainage of histic soils for agriculture are estimated at 8.7 million tons CO_2e. While *cropland* has the highest per hectare emissions, the emissions profile is dominated by emissions from *managed grassland*. 16% of emissions (1.4 million tons CO_{2e}) originate from sites within protected areas. Annual emissions from the drainage of humic soils were calculated at 1.8 million tons CO_2e. Similar to the histic sites, most emissions originate from *managed grassland*. Only 0.1 million tons CO_{2e} from the drainage of humic soils originate from sites within protected areas. Fig. 3 shows the emissions profile of carbon rich soils drained for agriculture in Ireland. The area in colour is equal to the total emissions.

3.2. Sensitivity analysis

The effect of assumptions on total emissions was tested for drainage depth, soil nutrient status and share of drainage within the *other pasture* category. For testing, assumptions in one category were varied while all

Table 2
Irish soil associations selected in scenario V1 (1XX) and scenario V2 (all). Areas with a gradient steeper than 12° are excluded.

Soil Association	Main Subgroup	Total Area	Histic Subgroups		Humic Subgroups	
		[10^3 ha]	[%]	[10^3 ha]	[%]	[10^3 ha]
1XX	Peat Soils	1,632.8	100	1,632.8	–	–
0660c	Humic Groundwater Gleys	56.0	13.6	7.6	49.5	27.7
0700b	Typical Surface-water Gleys	348.4	–	–	69.6	242.4
0700f	Typical Surface-water Gleys	10.1	–	–	69.0	7.0
0760f	Humic Surface- water Gleys	13.1	20.8	2.7	37.7	4.9
0843f	Stagnic Iron-pan Podzols	30.9	19.6	6.1	60.1	18.5

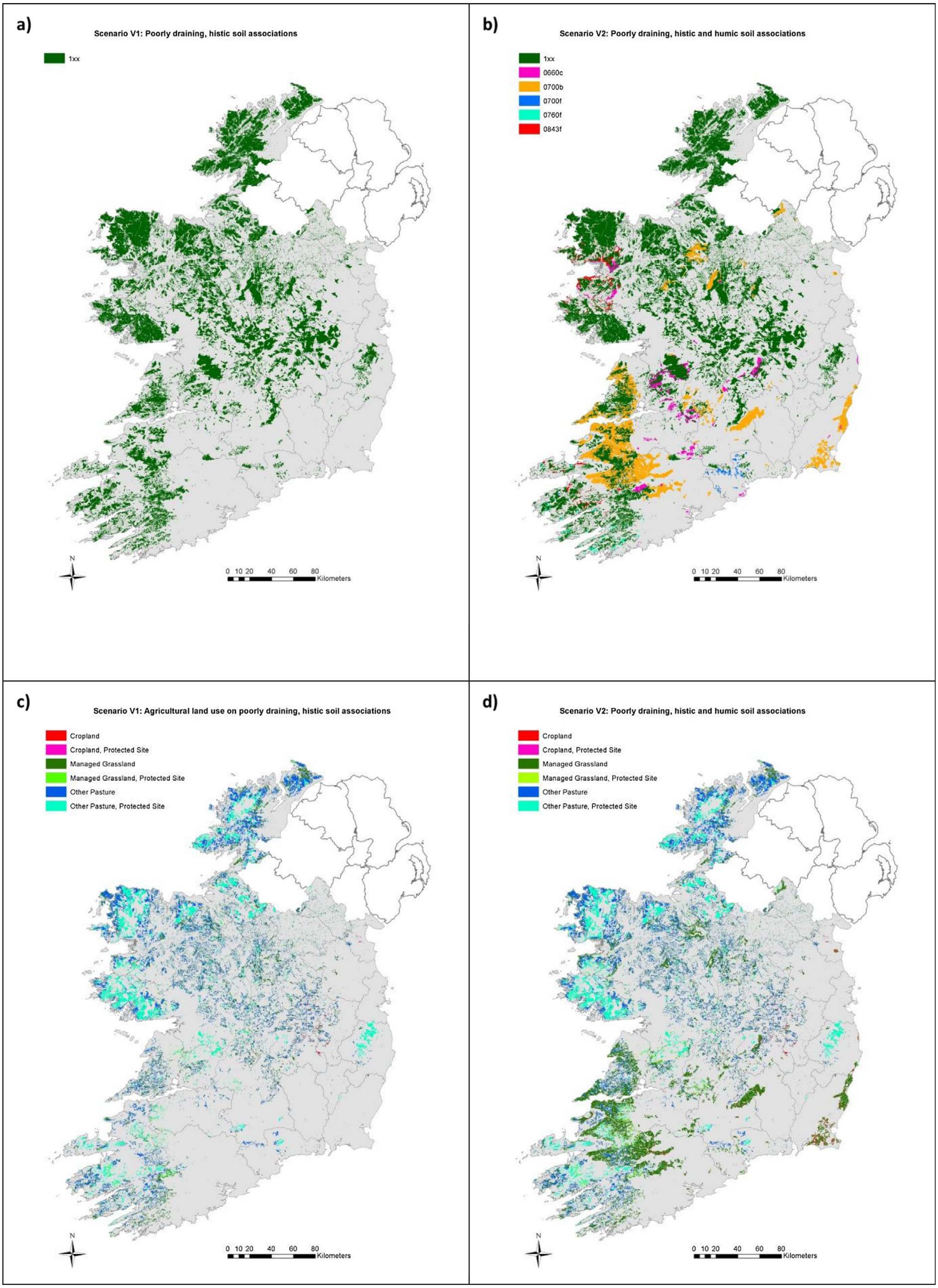

Fig. 1. (a–d): Distribution of poorly draining, histic (V1) and histic or humic (V2) soil associations in Ireland (a,b) and their agricultural land use (c,d).

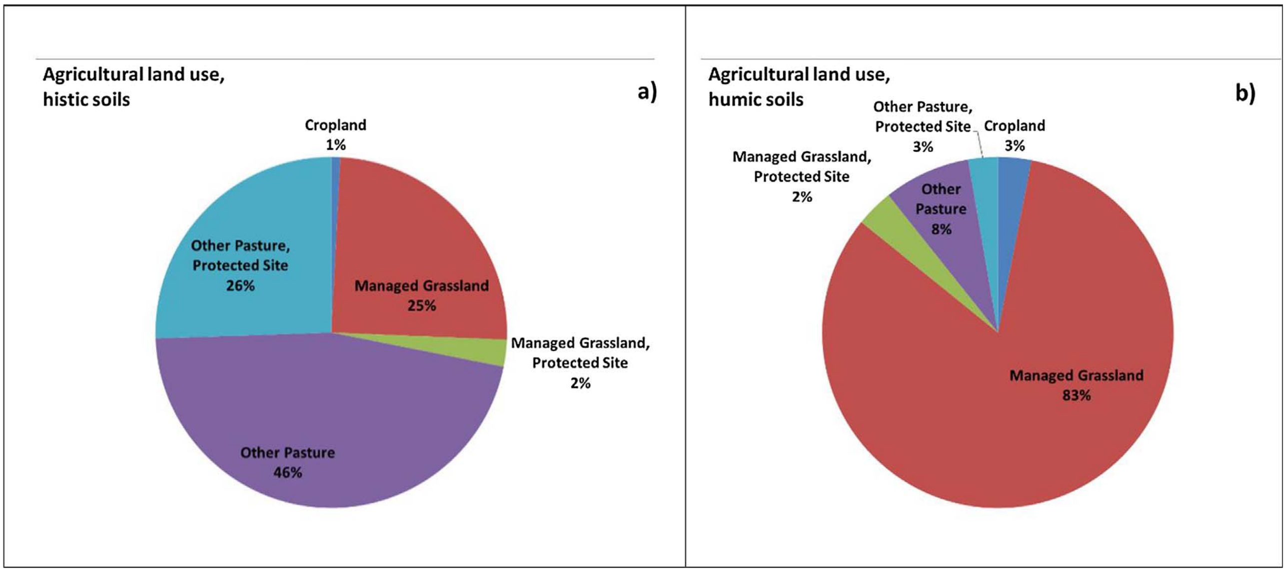

Fig. 2. (a,b): Distribution of agricultural land use within histic (a) and predominantly humic (b) soil associations in Ireland.

Table 3
Calculated emissions factors for humic soils drained for agriculture in Ireland.

Soil Type	Land Use	SOC Change 30 years [Mg C ha^{-1}]	CH_4 before drainage [kg CH_4-C ha^{-1} yr^{-1}]	CH_4 after drainage	EF_{CO_2} [Mg CO_2e ha^{-1} yr^{-1}]	EF_{CH_4}	EF_{Total}
Gortaclareen (760GN)	Cropland	−75.2	25.8	−2.3	9.2	−0.9	8.3
Gortaclareen (760GN)	Managed Grassland	−43.4	25.8	0.12	5.3	−0.9	4.4
Glenary (843GL)	Managed Grassland	−76.4	63.2	−1.1	9.3	−2.1	7.2
Knuttery (660KT)	Managed Grassland	−35.1	12	−1.77	4.3	−0.5	3.8
Ballynabreen (760BB)	Managed Grassland	−24.23	8.9	−0.45	3.0	−0.3	2.6
Puckane (660PU)	Managed Grassland	−39.5	15.8	−1.86	4.8	−0.6	4.2

Table 4
Calculated area and annual emissions of carbon rich soils drained for agriculture in Ireland.

Land use	Area [1000 ha]		Emissions [Tg CO_2e ha^{-1} yr^{-1}]	
	Histic Soils	Humic Soils	Histic Soils	Humic Soils
Cropland	7.9	14.8	0.3	0.1
Cropland, Protected Area	0.4	0.1	0.0	0.0
Managed Grassland	235.3	388.6	5.5	1.5
Managed Grassland, Protected Area	23.5	15.7	0.5	0.1
Other Pasture	65.9	5.4	1.5	0.0
Other Pasture, Protected Area	36.3	1.7	0.8	0.0
Total Within Protected Areas	309.0	408.7	1.4	0.1
Total Outside Protected Areas	60.2	17.5	7.3	1.7
Total	369.2	426.3	8.7	1.8

other assumptions were upheld. Stronger effects are expected for specific combinations.

Relative to the findings presented above, emissions for histic soils ranged from 86% under the assumption that all soils were considered shallow drained to 114% if all were deep drained. Assumptions on nutrient status had only a minor effect. Total emissions were 98% if all soils were considered nutrient rich and 102% if they were nutrient poor. Calculated emissions are lower under the assumption of nutrient rich soils because for the nutrient poor category IPCC default values do not distinguish between deep drained and shallow drained sites. Assumptions on the share of drainage within the *other pasture* category had the strongest effect, ranging from 82% if only 5% of this land use category were considered drained to 118% if 25% were considered drained.

For humic soils, only the sensitivity towards the assumed share of drainage in *other pasture* was tested. Total emissions were 99% if 5% of the land use category were considered drained and 101% if 25% were considered drained.

3.3. Potential greenhouse gas savings

Mitigation potentials were calculated with an assumed uptake rate of 50%, i.e. values assume that proposed measures are carried out on only half of the qualifying area identified above. This was done to account for technical or economic obstacles which may prevent rewetting in many cases.

Rewetting histic soils and restoring natural water table conditions would result in annual savings of 3.2 million tons CO_2e. Focussing only on cropland areas as emission hotspots would save 0.13 million tons CO_2e, while targeting only drained soils within protected areas would reduce emissions by 0.5 million tons CO_2e. Converting nutrient rich, *managed grasslands* from deep drained to shallow drained state would save 0.4 million tons CO_2e.

3.4. Economic effects of rewetting

Rewetting led to reductions in the number of dry days ranging from 116 days (*other pasture* within protected areas in *660c*) to 123 days (*other pasture* in *700f*). Resulting annual income losses for extensive beef farmers were estimated at 180–190€ ha^{-1}. However, this figure

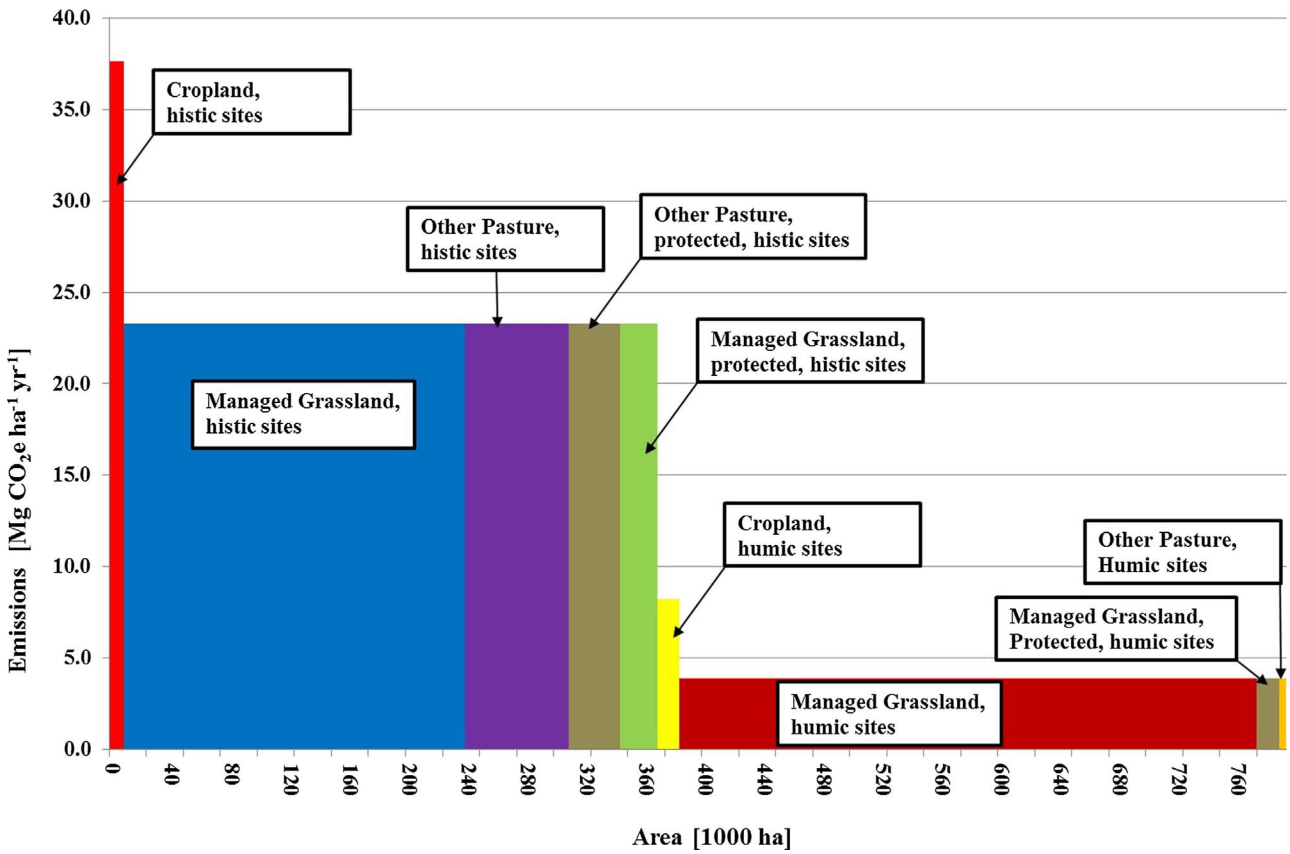

Fig. 3. Area of and GHG gas emissions from of carbon rich soils in Ireland drained for agriculture. The size of each coloured area corresponds to total emissions from the respective land use/soil combination.

must be considered a very rough estimate. Even with artificial drainage, carbon rich soils will often not achieve well-draining properties, so that the reduction in dry days following rewetting is likely to be less extreme. On the other hand, rewetting of sites may influence the quality of grass swards or necessitate major changes in farm operations. Furthermore, the act of disabling artificial drainage installations may incur additional costs.

4. Discussion

This study calculated area of drained histic and humic soils, drainage emissions and mitigation potential by combining the most up to date soil and land use information for Ireland. However, the use of soil associations poses challenges: While the peat association contains only histic soils, all predominantly humic associations contain a share of non-humic soil types. This study assumed land use to be spread evenly over all soils within the associations. However, it is also possible that farmland is concentrated on the better draining soils. For more precise estimates, further investigations are required. Additionally, at a scale of 1:250,000 local soil variations are simplified. Some of the small cropland hotspots that according to SIS are on peatland could be situated on pockets of other soil types. Finally, the lack of data on nutrient status, drainage depth and especially share of artificial drainage on *other pasture* posed severe challenges. However, sensitivity analysis showed that the assumptions made had only a limited effect on calculated of emission budgets.

While drainage of histic soils is doubtlessly associated with high GHG emissions as long as soils remain in a drained state (IPCC, 2014), the factors regulating the underlying biophysical processes and their changes over time are still not fully understood. Measured values may therefore differ strongly between sites and years. The IPCC emission factors are in some cases based on a very small number of study sites (only seven sites for CO_2 emissions from drained, nutrient poor grassland within the temperate zone) and can therefore only imperfectly represent local conditions. Renou-Wilson et al. (2014) investigated emissions from two extensively managed Irish grassland sites. For the nutrient rich site (drained for more than 60 years), they calculated CO_2 emission factors that were 96% of the IPCC default value, while for the nutrient-poor site (drained for more than 100 years), their factors were only 44% in a deep drained and 12% in a shallow drained part of the site. They concluded that the depth of drainage is of high importance for nutrient poor sites and that default emission factors may overestimate emissions from extensively managed, nutrient poor sites in Ireland. While UNFCCC encourages parties to progress from Tier 1 accounting towards developing emission factors more representative of national conditions, this would require Ireland to expand its current research on drainage of carbon rich soils. Should IPCC emission factors be found to overestimate emissions from nutrient poor sites in Ireland, then this would be positive from a global climate change perspective but would at the same time reduce opportunities for obtaining carbon credits from rewetting.

Drainage of cropland sites on histic soils results in the highest per hectare GHG emissions. However, because of the small spatial extent of this soil/land use combination in Ireland the contribution to total drainage emissions is only minor. On the other hand, the results of this study show that drained humic soils are a relevant emission source. More research is required to allow for their inclusion into national emission inventories. While the values of this study present a first estimate of emissions, modelling was based on an extreme drainage situation with a very high water table before drainage and a very low water table afterwards. Less extreme hydrological situations may result in lower emissions. However, the chosen land use settings after drainage represent only low management intensity. Higher intensities may also increase emissions. Furthermore, N_2O emissions were not included because they are strongly influenced by fertilizer applications, even though these emissions also increase with drainage. The biggest source of drainage emissions were *managed grasslands* on peat. These sites are responsible for 64% of emissions from drained histic soils. While only 16% of emission from histic soils originated from agricultural land within protected areas, these areas might be interesting targets for rewetting because additional policy tools are available there.

Calculated annual emissions from agricultural drainage (10.5 million tons CO_2e) where high when compared to Ireland's total agricultural emissions of 18.8 million tons CO_2e in 2014 (excluding emissions from land use [LULUCF]) (Duffy et al., 2014). While Schulte et al. (2013) modelled carbon sequestration under Irish grasslands for the year 2030 as 6.5 million tons CO_{2e} yr^{-1}, the results of this study indicate that including land use emissions into budget calculations would increase total agricultural emissions. This would also have implications for calculating the carbon intensity of produce from grass-based livestock production systems in Ireland.

High emissions from drained, carbon rich soils may also provide Ireland with options to meet national and international mitigation targets. However, under Tier 1 accounting only rewetting of histic soils will generate carbon credits. For those soils, decreasing drainage depth in deep drained, nutrient rich grassland soils is considered to reduce annual emissions by 12.1 Mg CO_2e ha^{-1}. Rewetting of deep drained grassland is considered to results in annual savings of between 19.3 and 21.1 Mg CO_2e ha^{-1}. The latter values are higher than the annual sequestration of 14.7 Mg CO_2e ha^{-1} found by Schulte et al. (2013) for newly planted forest in Ireland under projections for the year 2050. Furthermore, mitigation potential of forests decreases once biomass stock is established whereas benefits from rewetting remain constant.

Rewetting is not without problems, though. It can result in an initial increase in GHG emissions before emissions are reduced. Furthermore, it leads to phosphorous leaching, though this decreases with time (Kløve et al., 2017). Finally, rewetting of sites does incur economic costs that need to be reimbursed. However, apart from climate change mitigation, rewetting also carries significant benefits in terms of biodiversity and landscape conservation. While policy makers will need to consider the full array of costs and benefits, their discussion exceeds the scope of this paper.

5. Conclusion

Revised IPCC emission factors highlight the relevance of emissions from drainage of organic soils for agriculture while making full or partial rewetting more attractive as mitigation measures. Mitigation potential is high both on a per hectare basis and for Ireland as a county. One hectare of rewetted grassland is considered to have a higher mitigation effect than one hectare of newly planted forest. The estimated area of agriculture on drained histic soils in Ireland is 369,000 ha. If half of this area was rewetted, annual GHG savings would amount to 3.2 million tons CO_2e. While emissions from drained humic soils are lower than those of histic soils, calculated annual emissions were relevant at 1.8 million tons. Emissions from humic soils should be considered in new drainage projects and research should seek to establish emission factors to integrate them into national GHG inventories. Further research should also explore the cost effectiveness, as well as trade-offs and co-benefits of rewetting.

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